Discussion on Design

Nature Aware Design

The Convergence of Form and Function

Workshop 2, Benchmarking of new
Beyond CMOS device/design concepts,
Hotel Divani Caravel, Vassileos Alexandrou Av.2, Athens, Greece

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13-14 October 2011

What can we learn from Nature?

A hierarchy of design and fabrication methods

Current Semiconductor Methods

Living Systems

Subtractive Patterning

Regular Self Assembly

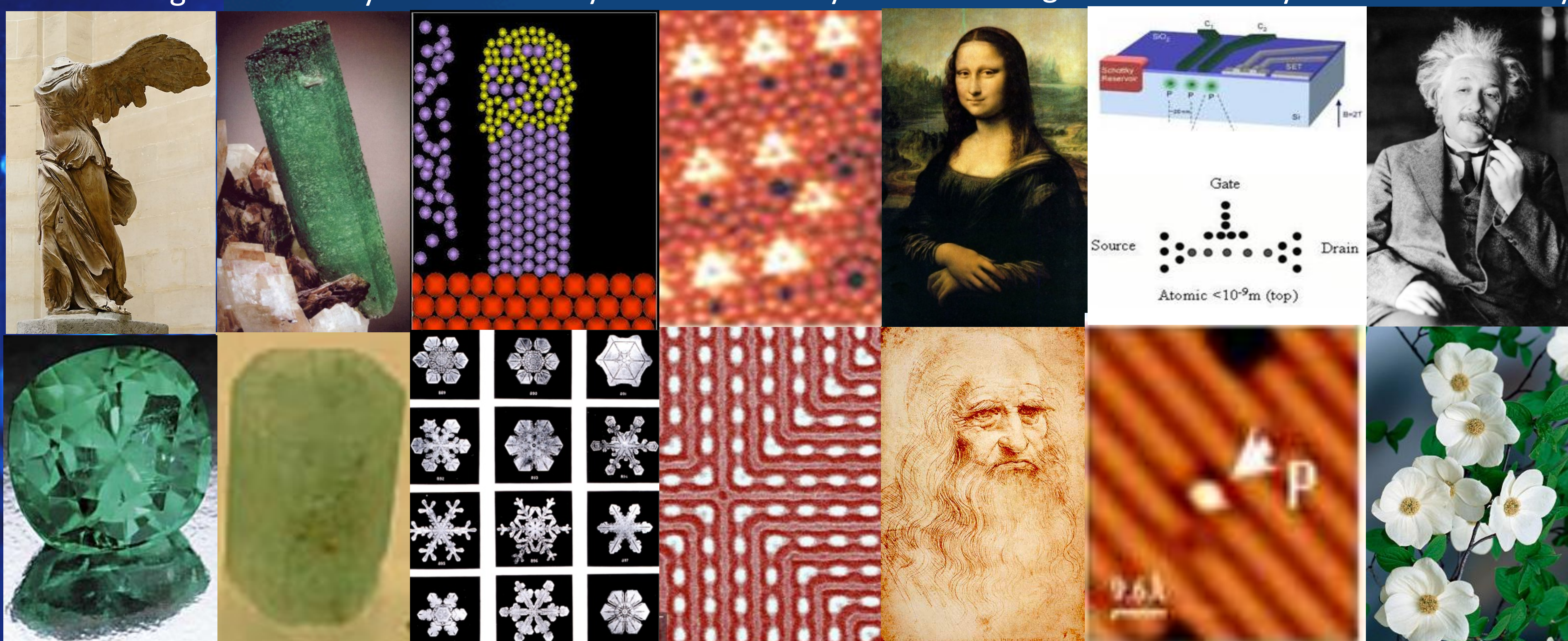
Field Assisted Assembly

Directed Self Assembly

Serial Patterning

Deterministic Assembly

Programmed Self Assembly

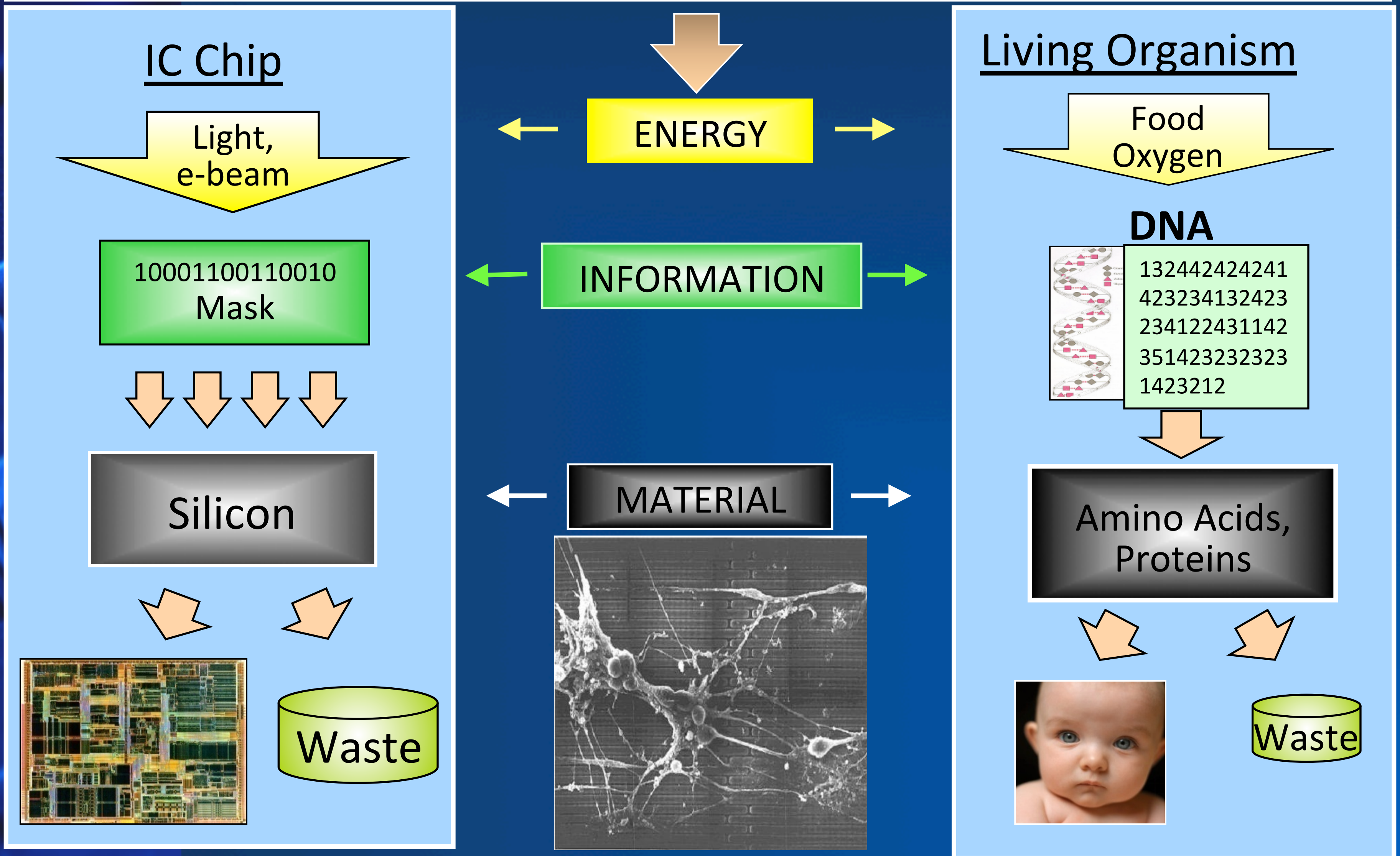


Increasing information content, complexity

and fabrication control required

Subtractive Versus Programmed Assembly

Complex Matter = Energy + Information + Material



Comparison of subtractive versus bio-assisted assembly/patterning

D. Herr (2000)

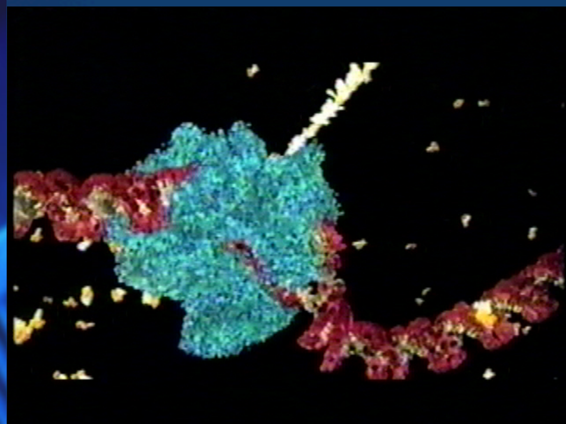
Comparative metrics	Fab output [Subtractive patterning]	Growth of a baby [Programmed assembly]	Programmed assembly advantage
Bits patterned per second	<1.3E9 bits/s	>1.5E+17 amino acid/s	>1E+8
Energy required per bit	>2.1E-8 J/ bit	<6.6E-17 J/amino acid	>3E+8

[1] Subtractive processing: Form in-place

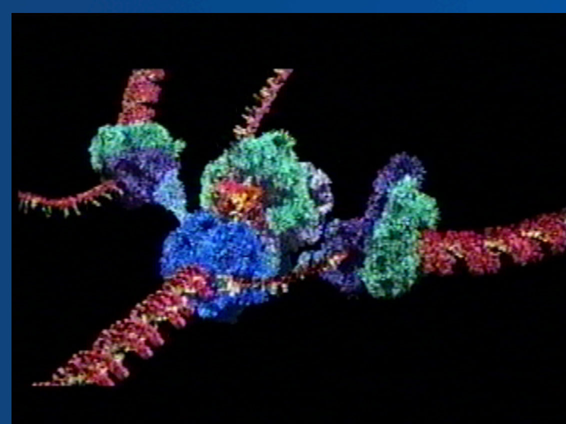
[2] Bio-assisted assembly: Grow remotely and place

The machinery of life

DNA Transcription



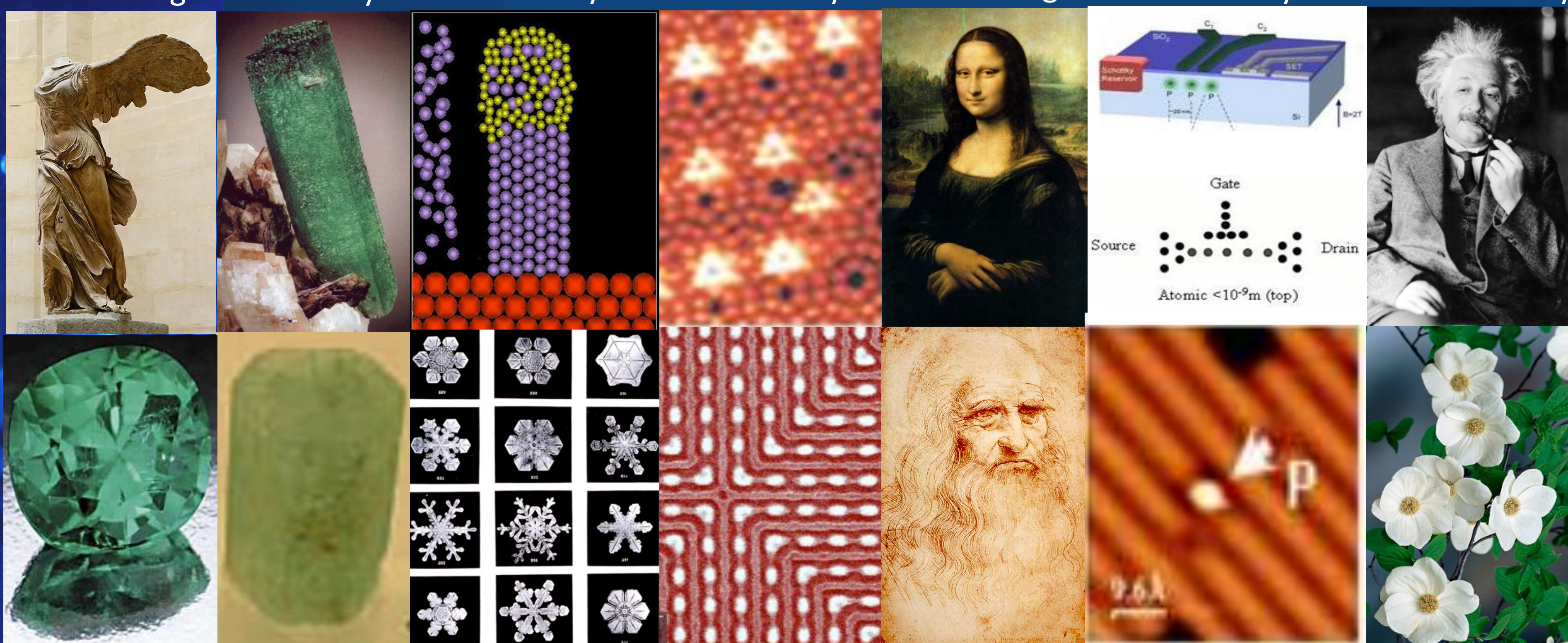
Protein Translation



DNA Replication

What can we learn from Nature?
A hierarchy of design and fabrication methods

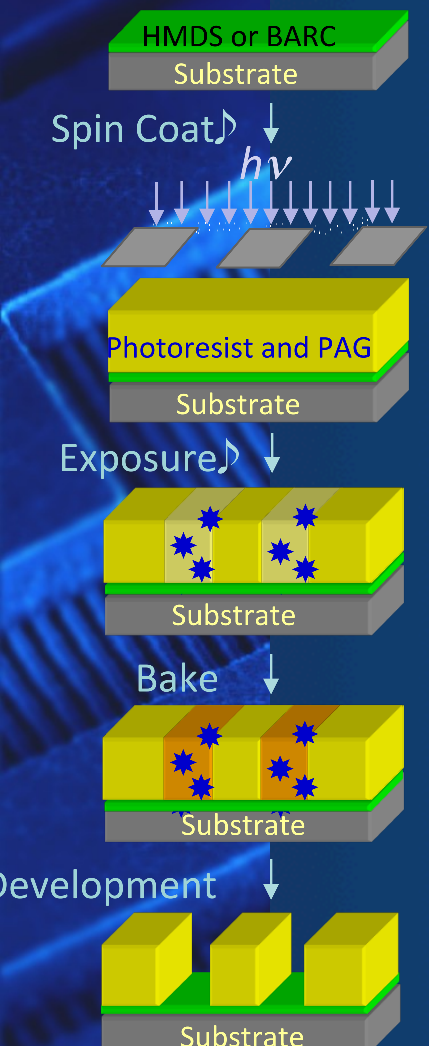
Subtractive Patterning | Regular Self Assembly | Field Assisted Assembly | Directed Self Assembly | Serial Patterning | Deterministic Assembly | Programmed Self Assembly

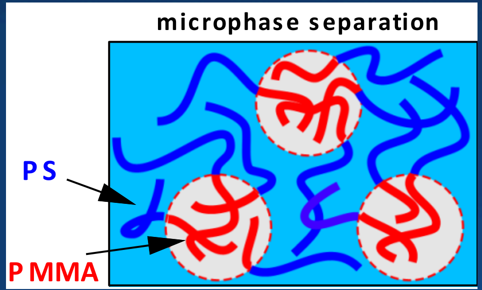


Increasing information content, complexity
and fabrication control required

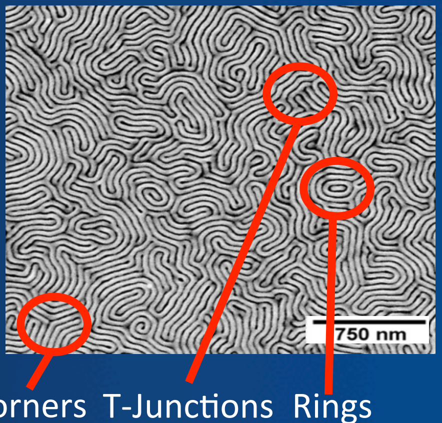
Directed self assembly:
Form patterns in place

Photolithography

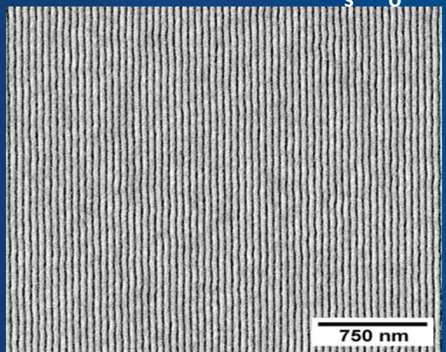




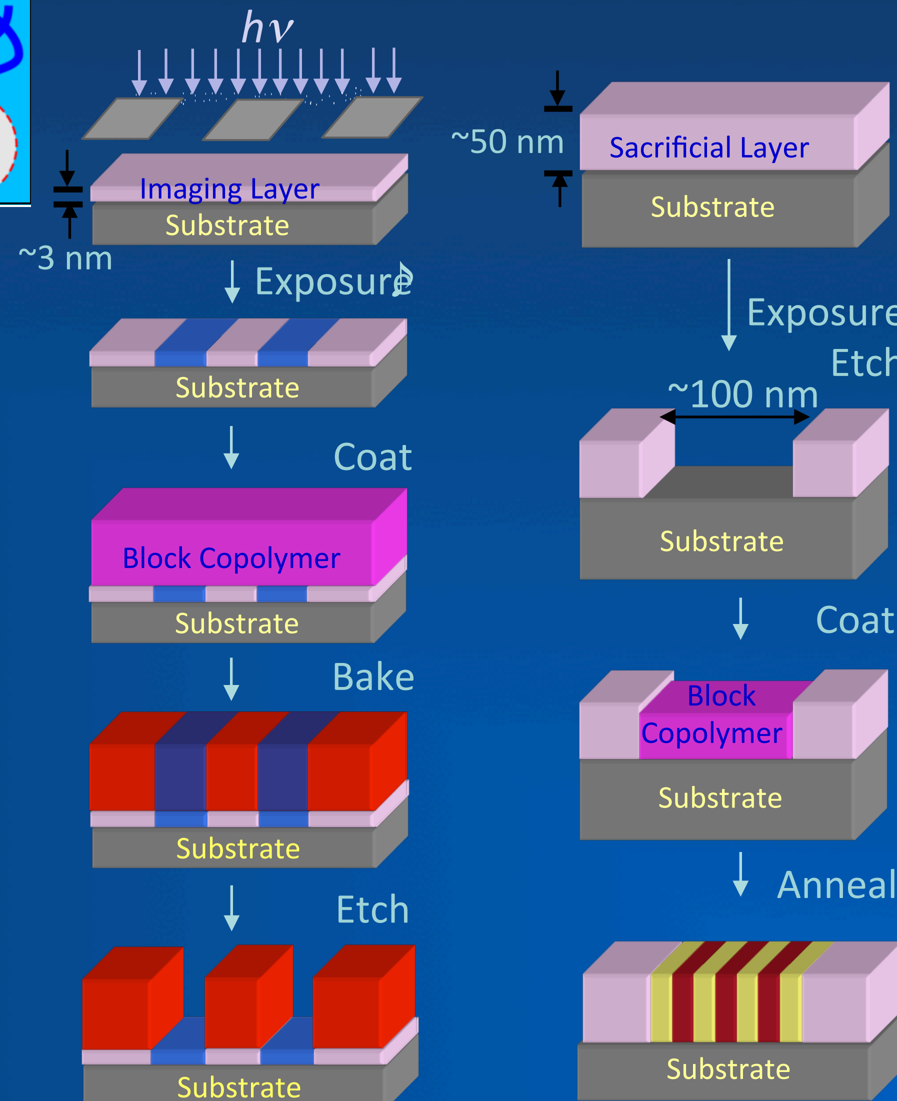
Unpatterned Surface



Patterned Surface $L_s=L_o$

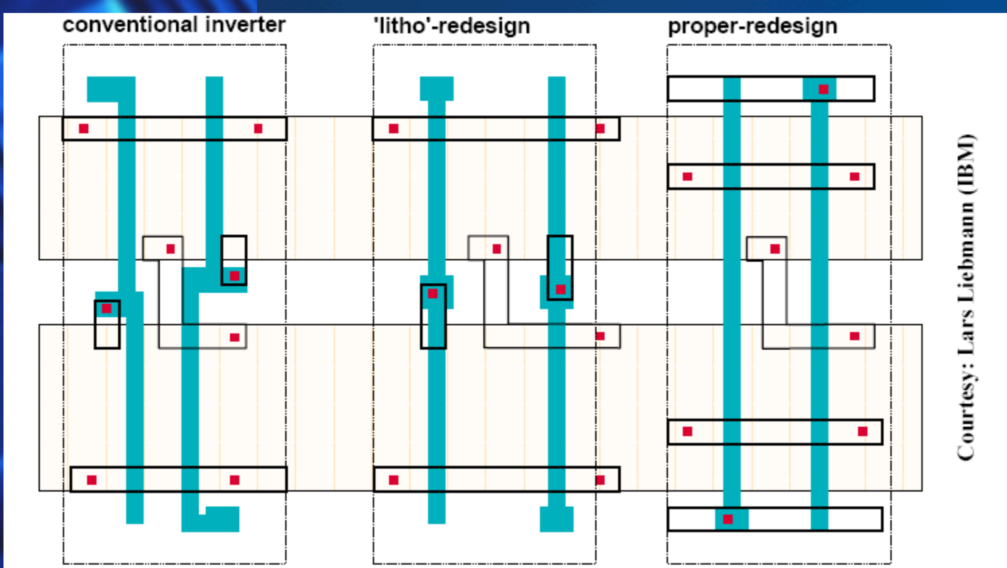


Directed Self-Assembly

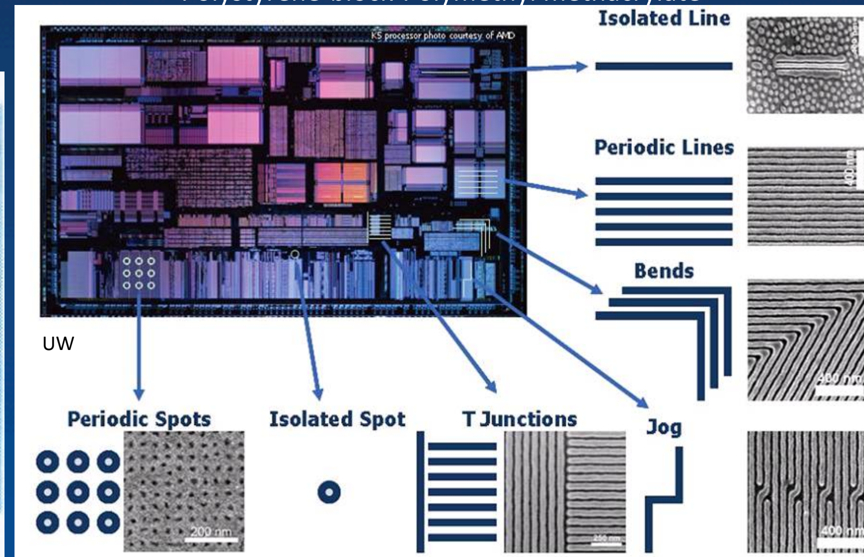


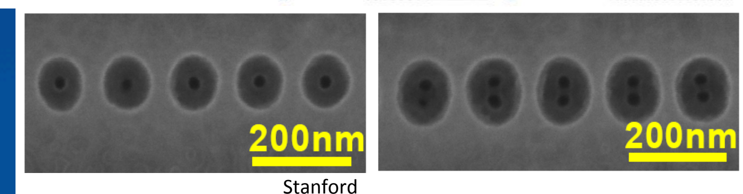
Directed Self-Assembly: A Synergistic Patterning Option

The Pattern Fidelity Challenge



Polystyrene-block-Polymethyl methacrylate





Some Benefits:
- ❑Lower LER and variability
- ❑Enhanced Resolution
- ❑ Self Healing

A Key Challenge:
- ❑Defects

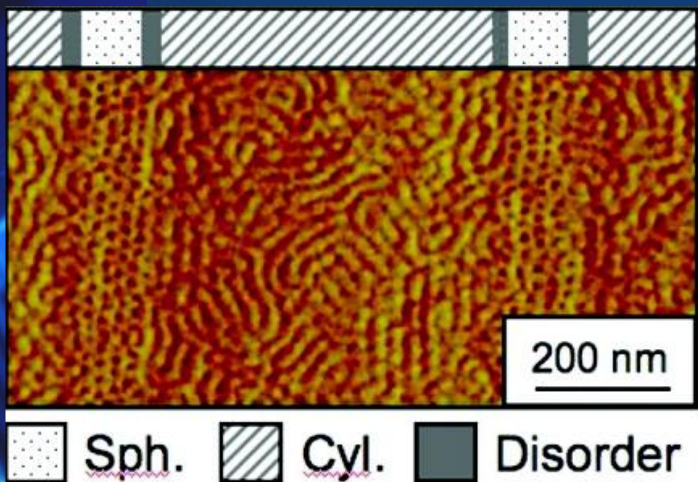
An estimate of nucleic acid 'bio-bit' defect rates

- Consider a DNA string as the biological equivalent of a chip, with a nucleic acid as the biological equivalent of a bit.
- Given :
  - The DNA defect rate of ~1E-4 represents a 99.999% 'bio'-chip yield.[1]
  - A double stranded DNA molecule contains ~1E9 to 2E9 nucleic acids
- Then, nucleic acid 'bio-bit' error rates are ~1E-13.
  - Where the bio-bit error rate =~1E-4errors/DNA*1E-9DNA/nucleic acid.
- Additionally, bio-error correcting mechanisms place **an upper limit on the net defect rate for DNA fabrication as < 1E-14**.
  - Simulations by de Pablo suggest that the intrinsic defect rate for directed self assembly is <<1E-14.

[1]M. Lynch: Evolution of the mutation rate. Trends Genet. 26(8), 345 (2010); M. Lynch: The rate, molecular spectrum, and consequences of human mutation. Proc. Natl. Acad. Sci. USA. 107, 961 (2010); 246. J.F. Crow: The origins, patterns and implications of human spontaneous mutation. Nat. Rev. Genet. 1(1), 40 (2000).

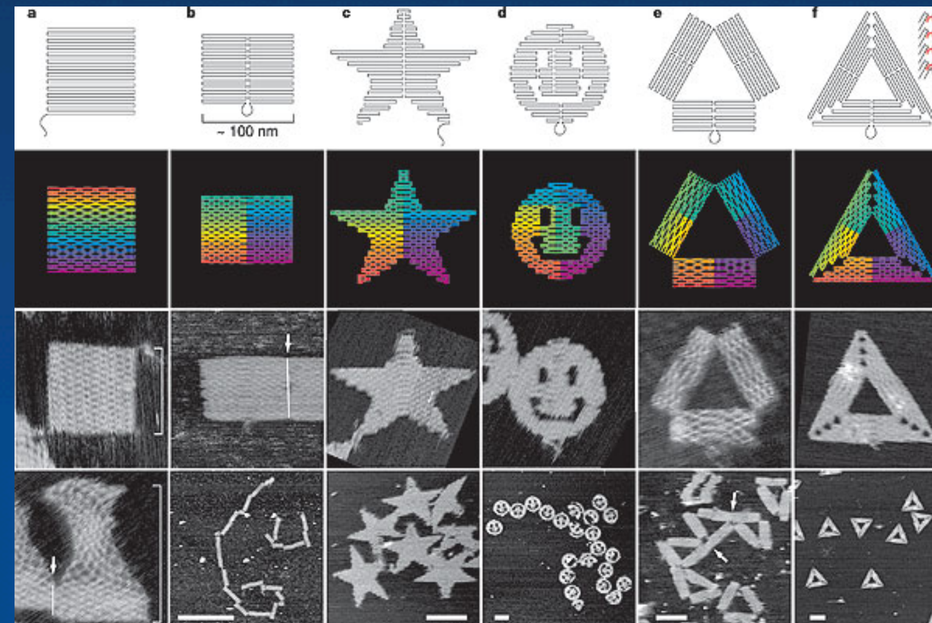
Resolution and complexity

Due to unique crosslinking ability of PaMS-b-PHOST, multiple morphologies on one wafer are possible

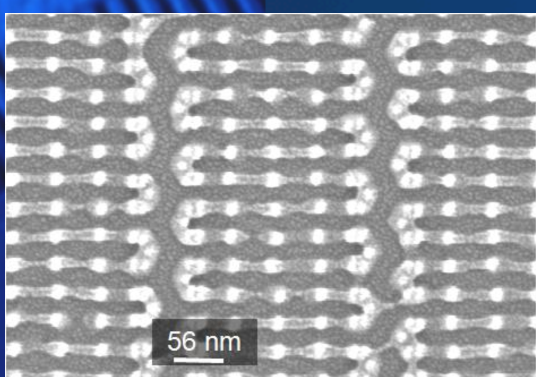


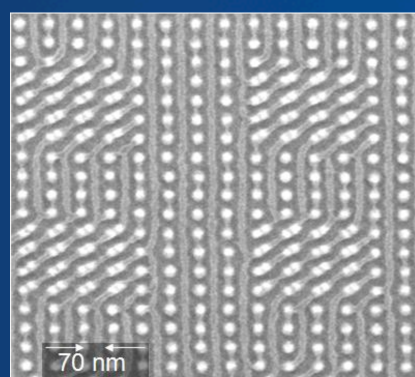
(Cornell and IBM)

Size of Molecular Scaffolds

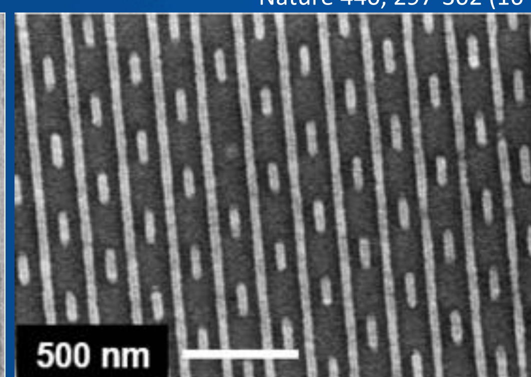


Folding DNA to Create Nanoscale Shapes and Patterns, Paul W. K. Rothemund, Nature 440, 297-302 (16 March 2006)

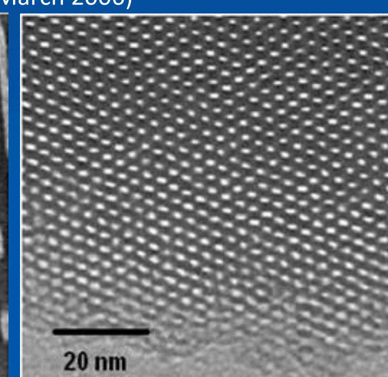




Directed Assembly of Complex Shapes
(MIT)



Trimmed DSA patterns
(MIT LL)



3 nm Silicate pores
(UMA-A)

A Strategic Joint Challenge/Opportunity for Materials Scientists, Designers and Others

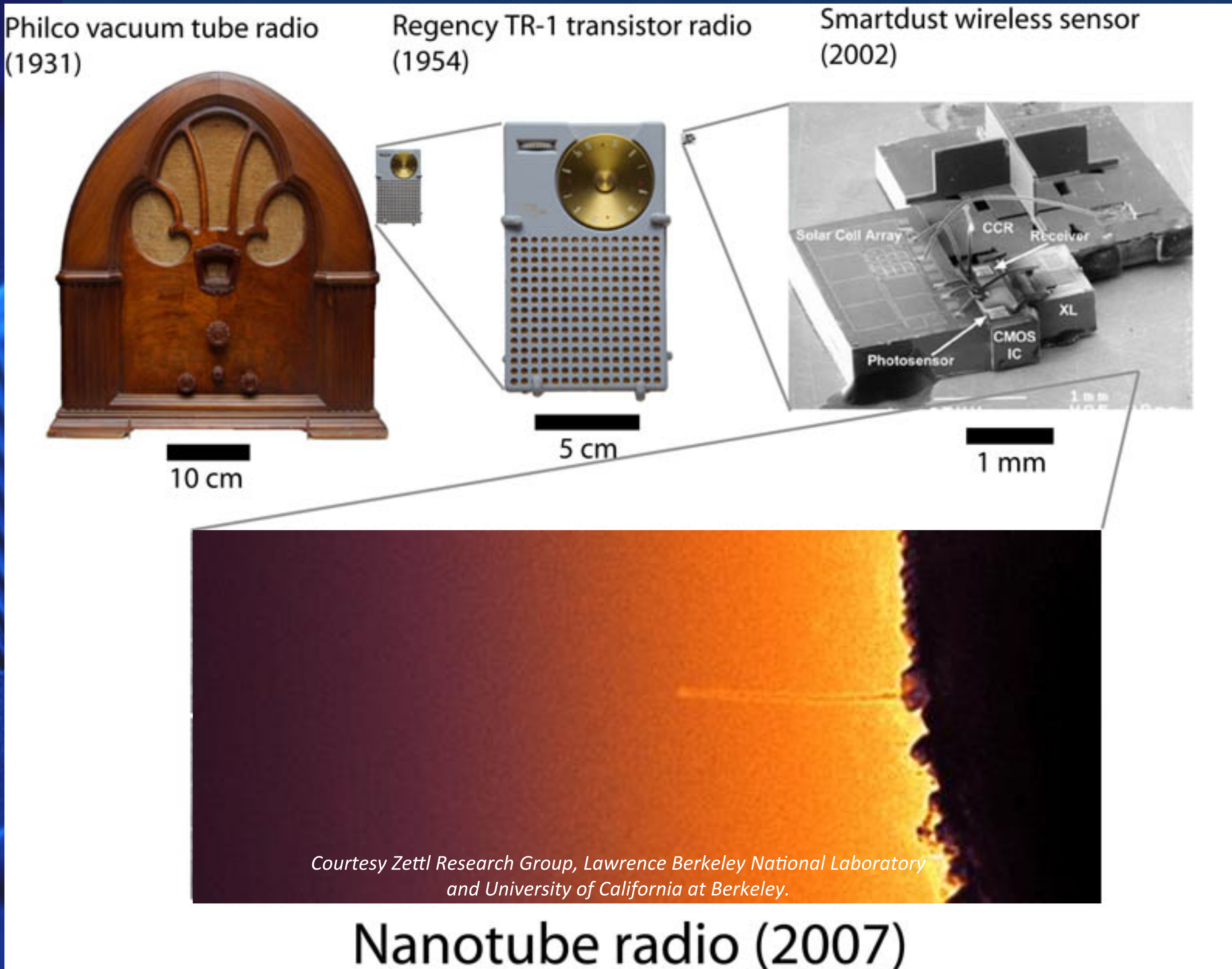
We need materials options that circumvent Moore's Second Law

What is the next evolutionary step?

Smart resists, with designed dimensional, placement, and alignment control?

With electronically useful functionality?

Example of a Functional Material: Nanotube Radio



Nature Inspired Design:
The Convergence of Form and Function

Fabrication and Integration of Low Power D/A/MS Application Specific Materials

Example: Receptor Cells of the Inner Ear

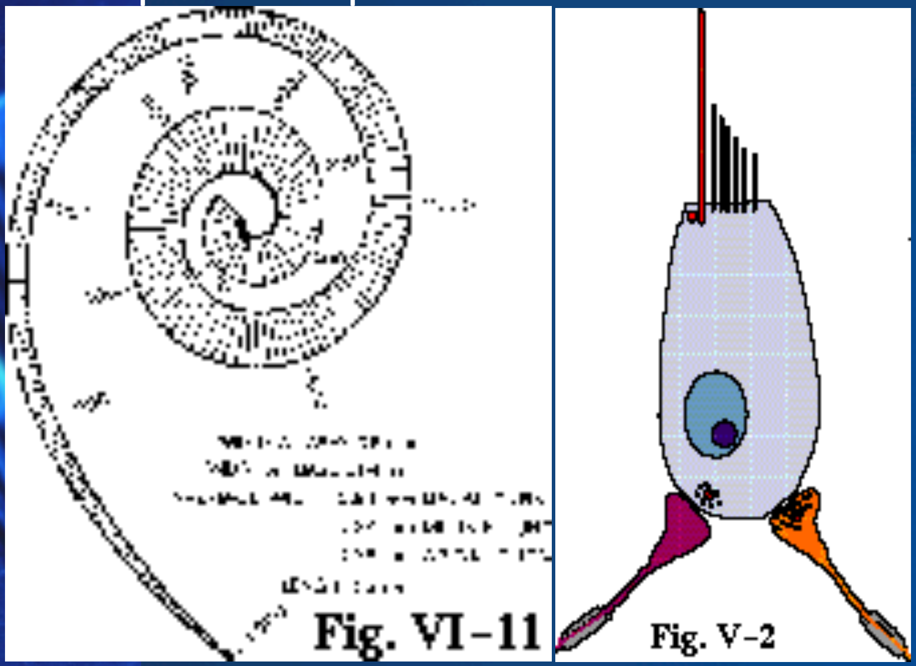


Fig. VI-11 Fig. V-2

Source: http://www.neurophys.wisc.edu/h&b/textbook/chap-5.html

What can we leverage from these natural structures that might enable new families of selective sensors?

Can we fabricate hybrid structures, such that different regions respond maximally to different input frequencies based on the local physical properties?

The ultimate functional diversification challenge: Proof of concept demonstration

Consider a neutrophil chasing a S. aureus in our blood stream:

This represents an example of a distributed intelligent network of autonomous systems, composed at the nano-level, with adaptive emergent behaviors

[Courtesy of Chih-Ming Ho, UCLA]

Key Messages

- Nature's ability to leverage miniaturization and functional diversification provides clues for developing **convergent nature aware design and fabrication options**.
- This is a good time for the research and development communities to **question some of our basic assumptions about variability, cost, power, and functionality** in the micro- and nano- domains.
- Challenge: Can potential **nature inspired material and design solutions** be identified and matured in time to **impact key insertion windows?**

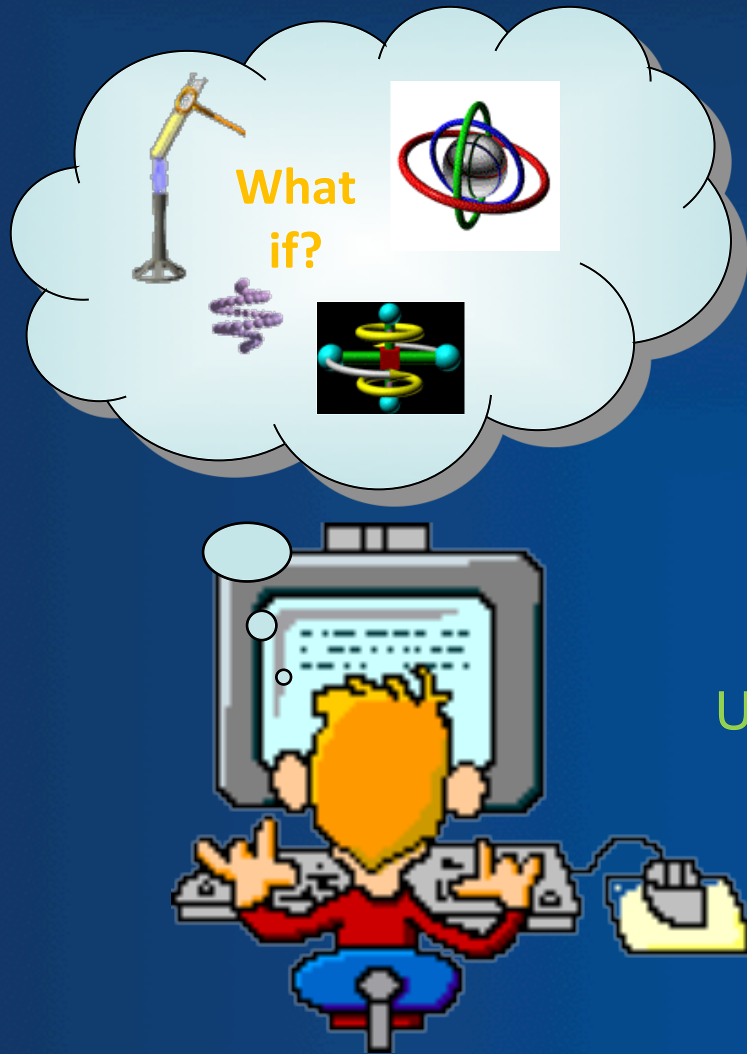
Discussion on Design: Nature Aware Design

Technology	Directed Self Assembly: Beyond CMOS Resists
Gain Throughput Signal/Noise ratio Non-linearity	NA NA Material driven
Speed Power consumption	NA NA
Architecture/Integrability (Inputs/outputs, digital, multilevel, analog, size etc.)	Compatible with CMOS and post CMOS patterning methods.
Other specific properties	Low energy processing; Non-regular patterns feasible; Compact models are needed.
Manufacturability (Fabrication processes needed, tolerances etc.)	Benefits demonstrated: Low LER[<1.9 nm 3σ]; self healing; density multiplication; high resolution; high throughput [25 wafers @ 2-3 minute anneal; registration error <6 nm over several μms. Concern: Defectivity demonstrated @ <25/cm^2; theory <<1E-12.
Timeline (When exploitable or when foreseen in production)	ITRS Lithography Potential Solution insertion window: 2018-2019; Likely 1st insertion option: mass storage; Several companies are exploring earlier insertion dates.

Discussion on Design: Nature Aware Design

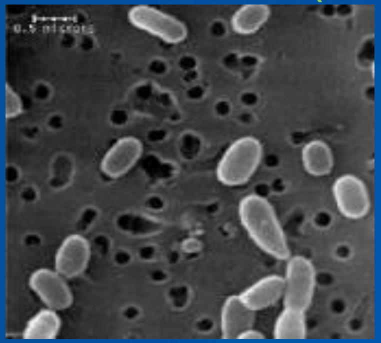
Technology	Beyond CMOS Application Specific Materials
Gain Throughput Signal/Noise ratio Non-linearity	TBD TBD Application specific
Speed Power consumption	TBD TBD
Architecture/Integrability (Inputs/outputs, digital, multilevel, analog, size etc.)	Target ITRS identified More-than-Moore applications; Need foundational understanding of material structure-property-relationships and material-by-design capability
Other specific properties	Increased material complexity;
Manufacturability (Fabrication processes needed, tolerances etc.)	Should be compatible with low energy, high throughput CMOS and post CMOS patterning, except where flexible applications are warranted;
Timeline (When exploitable or when foreseen in production)	Potential insertion window: Beyond 2018 [Guardian Angels suggest insertion at or beyond 2022]

How small can we go?



Thank You

Ultra-micro-bacteria (~200 nm)



Extracted from a glacial ice core sample, 120,000 years old Miteva (2005)

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